

Global amount of dust in the universe

Masataka Fukugita

Institute for Advanced Study, Princeton NJ08540, U.S.A. and

Institute for Cosmic Ray Research & Institute for the Physics and Mathematics of the Universe,

University of Tokyo, Kashiwa 2778582, Japan

Accepted Received

ABSTRACT

It is pointed out that the total amount of dust in the Universe that is produced in stellar evolution in the entire cosmic time is consistent with the observed amount, if we add to the dust amount inferred for galactic discs the amount recently uncovered in galactic haloes and the surrounding of galaxies in reddening of the quasar light passing through the vicinity of galaxies. The inventory concerning the dust closes. This implies that dust produced from stars should survive effectively for the cosmic time, and that a substantial amount of dust is produced in the burning phase of evolved stars of intermediate mass.

Key words: ISM: dust, extinction; cosmology: miscellaneous

1 INTRODUCTION

A significant amount of gas is ejected into interstellar space during the life of stars by stellar wind mass loss and at supernova explosions. Gas contains heavy elements either taken from the initial gas or produced during the stellar evolution. A significant fraction of heavy elements condenses to form dust. Although the mechanisms to produce dust have not been well understood, the net amount of dust produced from gas with heavy elements can be estimated with some confidence.

Reasonable estimates are available as to how much material is processed by stars by integrating the star formation rate as a function of cosmic time. Using recent compilations of the star formation rate, we estimate that the total amount of material (fuel) processed lies between $\Omega_{\text{fuel}} = 0.004$ and 0.010 (e.g. Fukugita & Peebles 2004, hereafter FP04; Hopkins and Beacom 2006; Fardal et al. 2007; Nagamine et al. 2006; Ouchi et al. 2009; Bernardi et al. 2010; Bouwens et al. 2010), assuming the Chabrier initial mass function (Chabrier 2003). We refer to this amount as the fuel. These two numbers represent the curves that pass through close to the lower and upper parts of the star formation rate plot¹. We remark that the uncertainty seen in the two numbers largely arises from the normalisation in low redshift rather

than apparently more ambiguous high z behaviours, for instance, whether the star formation rate declines at $z > 3$ as favoured by recent observations (Ouchi et al. 2009; Bouwens et al. 2010). The time span is short at higher redshift and the integrated contribution to the total amount of stars from $z \geq 2$ is roughly $< 20\%$, so that the high redshift behaviour is not important in our argument².

On the other hand, stars and their remnants, white dwarfs, neutron stars and black holes, that reside in galaxies are estimated to be

$$\Omega_{\text{star}} = 0.0030 \pm 0.0005 \quad (1)$$

(Fukugita & Peebles 2004; hereafter FP04; 10% upward shift is applied to agree with the initial mass function we use here). Similar estimates have been made by a number of authors (e.g., Shankar et al. 2004; Oohama et al. 2009; Bernardi et al. 2010), and they fall in the range indicated by the two numbers. There is a gap between the two numbers, Ω_{fuel} and Ω_{star} . This may primarily be ascribed to the material shed by stars during the evolution, as either stellar winds or supernova explosions, whereas there still remains a gap between the two values is left as a problem in the future.

Taking the initial mass function of stars given by Chabrier, we estimate that the gas fraction shed by stars during the evolution is 0.60 times the mass locked into stars and stellar remnants, as summarised in what follows. Therefore, the amount of baryons consumed in star formation is $\Omega_{\text{fuel}} = 0.0030 \times 1.60 = 0.0048$, which agrees with the

¹ We take as our fiducial the Chabrier initial mass function for $M < 1M_{\odot}$ and the Salpeter initial mass function for $M > 1M_{\odot}$. Chabrier takes the mass function slope -2.30 rather than -2.35 of Salpeter at a higher mass (he revised to -2.35 in his later version). The difference in total mass is about 5%, which is smaller than the uncertainty that concerns us here. We also note that the initial mass function used in FP04 is close to the Chabrier initial mass function, but gives the total mass 10% smaller than the Chabrier.

² The normalisation at low redshift, which varies among the authors, is the major source of the uncertainty. Also note that the star formation rate increases significantly between $z = 0$ and $z = 0.1$.

amount of fuels estimated from the integration of the star formation rate at its lower value of the integral of the star formation rate. In the following argument we assume the total amount of the fuel is $\Omega_{\text{fuel}} = 0.005$ for the consistency of the argument. This leads to the full consistency of the stellar baryon and energy budget, as noted in FP04, including the stellar light emission, supernova rates and heavy element production, while the accounting must be improved especially as to the star formation rate. At the upper edge of the star formation rate, the integral of the star formation rate seems to overshoot the stars which we see today.

In our calculation of the dust production we use the final mass-initial mass relation for white dwarfs (Serenelli & Fukugita 2007; see also Salaris et al. 2009), the mean mass of which is $0.62M_{\odot}$ for main sequence stars with the mass $1 - 8M_{\odot}$, when averaged over the Salpeter mass function. For neutron stars we adopt $1.35M_{\odot}$ for the main sequence mass $8 - 25M_{\odot}$, and $7.5M_{\odot}$ for putative stellar black holes for the main sequence mass $25 - 100M_{\odot}$ (Heger et al. 2003). The remnant black hole mass is highly uncertain, but the fuel that ends with black hole is 8% and the remnant mass is only 1.4% the fuel mass with our adopted black hole mass: the large uncertainty in the remnant black hole mass is not important for our considerations. For completeness let us quote that 11% of eq.(1) are partitioned into white dwarfs, 8% are substellar and neutron stars are 2%.

We take this simple model as the base to estimate the amount of dust produced in stellar evolution. FP04 have calculated that the observed extragalactic background light amounts to the energy density $\Omega = 5.1 \pm 1.5 \times 10^{-6}$ where the optical and far infrared contribute by 2:1, with a 7% addition by neutrinos, and that the binding energy in heavy element we observe today is altogether $\Omega = -5.7 \pm 1.3 \times 10^{-6}$, including nuclei locked in or sequestered from stars. This nearly balances the energy in the extragalactic background light with the error arising from the two vastly different accounting kept in mind. It was also shown that the energy output from stars is expected to be $\Omega = 5.4 \times 10^{-6}$ for the given fuel that amounts to $\Omega = 0.005$. We note that there is no missing metal problems at least at $z = 0$, but note that 80% of heavy elements are locked in white dwarfs and 25% of ‘metals’ is sequestered in neutron stars and black holes.

In addition, it was also shown (FP04) that the present day rate of core collapse supernovae $0.0079^{+0.0024}_{-0.0039} (100\text{yr Mpc})^{-3}$ obtained from the star formation rate, integrating over the initial mass function from $8M_{\odot}$ to $100M_{\odot}$ agrees with the observed rate $0.0076^{+0.0064}_{-0.0020} (100\text{yr Mpc})^{-3}$ albeit with large errors in the observed value. These supernovae produce iron at $\Omega_{\text{Fe}} = 3.6 \times 10^{-6}$. A similar estimate of type Ia supernovae, with their normalisation adjusted to the present rate, gives the iron abundance 2×10^{-6} , which results in the total iron abundance $\Omega_{\text{Fe}} = 6 \times 10^{-6}$, when added, in agreement with the estimate of the cosmic iron abundance $\Omega_{\text{Fe}} = 6.3 \times 10^{-6}$ for materials which are not locked up in stellar remnants, or sequestered from them. The network of consistencies among the numbers shown here points towards the validity of this simple framework, concerning the hydrogen fuels consumed and the heavy element produced. This tempts us to apply a similar consideration to the amount of cosmic dust, which was not done in FP04.

It is yet poorly understood where and how dust is pro-

duced, and how long does it survive. The calculation we show in this paper, based basically only on the final and initial mass budgets, circumvents these poorly understood aspects and uncertainties. It gives accounting of dust produced, which is subject to much less uncertainties. We take the Hubble constant $H_0 = 70\text{km s}^{-1}\text{Mpc}^{-1}$, matter density $\Omega_m = 0.3$ in a flat universe whenever necessary.

2 THE AMOUNT OF COSMIC DUST

We take the traditional elemental abundance given by Grevesse and Sauval (2000), while noting that more recent solar abundance estimate by Asplund et al. (2005) leads to somewhat a smaller abundance of heavy elements. The adoption of the new abundance changes some details of our results, but our conclusions are unaffected. The initial solar abundance is $Z_{\odot} = 0.019$ or $Z/X|_{\odot} = 0.027$ using the Grevesse and Sauval table with the present day solar abundance $Z/X|_{\text{surface}} = 0.023$. with the aid of the solar model of Bahcall et al. (2001). The solar abundance would be reduced to $Z_{\odot} = 0.012$ if we adopt the revision by Asplund et al., 40% smaller than the Grevesse and Sauval value.

The mean metallicity correlates with luminosity of galaxies (Tremonti et al. 2004). When we integrate the metallicity over the luminosity function we obtain the cosmic average $\langle Z \rangle = 0.83Z_{\odot}$.

We assume that refractory elements, Si, Fe and Mg in interstellar gas or those ejected into interstellar gas all *eventually* condense to solids. The condensed material is not precisely identified, but it is argued that they form effectively $\text{Mg}_x\text{Fe}_{2-x}\text{SiO}_4$ (the composition of olivine, forsterite or fayalite) with $x \approx 1$ and $\text{Mg}_x\text{Fe}_{1-x}\text{SiO}_3$ (enstatite) for a lesser amount (Weingartner & Draine 2001). The solar elemental abundance of these three refractory elements is similar, 32–38 ppm per hydrogen, and hence are almost saturated if all Si is condensed to the olivine composition. Observationally, these elements are known to be highly (> 90%) depleted from interstellar gas. We assume that these elements condense into dust, and they take oxygen by 20% locked up in the silicate.

The other prominent component of dust is carbonaceous material, likely including polycyclic aromatic carbon for small grains to graphite for large grains. The estimate for the fraction that condense to carbonaceous material varies. We take the fraction of condensation to be $50 \pm 25\%$, consistent with the value taken by Weingartner & Draine (2001) (Weingartner & Draine 2001).

Adding the two components we obtain the dust to metallicity mass ratio

$$\eta = \text{dust}/Z \simeq 0.28 \pm 0.07, \quad (2)$$

where the error dominantly arises from the two choices of the silicate and partly from the assumed amount of carbon that condenses into dust. With the solar metallicity for the Milky Way, we then obtain

$$\text{dust}/\text{HI} = 1/(135 \pm 30) \quad (3)$$

in agreement with the value adopted by models of dust to explain interstellar reddening (Mathis et al. 1977; Weingartner & Draine 2001) and also with observations. Draine et al. (2007) estimated it to be $1/140$ for the Milky Way, and find

for other galaxies that this fraction varies between 1/100 and 1/400 with the median 1/190 for SINGS sample of galaxies. The fiducial value of 1/100 is usually taken as the dust/HI mass ratio in the Milky Way. We assume that the heavy elements present in the interstellar matter condense into dust with the fraction given by eq. (2), and dust to HI ratio is universal in HI regions.

The HI survey (Zwaan et al. 2005; Zhang et al. 2008) and the H₂ survey (Keres et al. 2003) give the cosmic value for the sum of atomic and molecular hydrogen to be

$$\Omega_{\text{HI+H}_2} = 5.35 \pm 0.87 \times 10^{-4} \quad (4)$$

where HI : H₂ \approx 0.70 : 0.30. With the assumption that dust resides in the HI region and the hydrogen to dust ratio is universal we estimate the global dust abundance in galactic discs,

$$\Omega_{\text{dust disc}} = 4.0 \pm 1.3 \times 10^{-6} \quad (5)$$

This is compared with the dust abundance estimated from obscuration due to galaxies in a galaxy survey (Driver et al. 2007), $\Omega_{\text{dust galaxy}} = 3 \times 10^{-6}$.

Dust may coagulate to form planets and may be depleted. The amount we estimated, however, is disturbed little by the planets formation, while they are not entirely negligible. Marcy (2005) estimated that 12% of nearby FGK stars have detected Jupiter-like planets within 20 AU with the planet mass distribution $dN/dm \sim m^{-1}$. In the recent analysis Johnson et al. (2010) indicate that the fraction depends on the mass of the central star and drops to 3% for M dwarfs, which dominate the stars in number. Taking Figure 4 of Johnson et al. we estimate that 0.052 planets formed per 1 M_{\odot} of fuel consumed. Here we extend the range of stars to span the full range of M and A stars, by slightly extending the observed range which lies between 0.25 to 2 M_{\odot} .

The observed planets are of the Jupiter type, which is dominated by hydrogen and helium gas. What concerns us here is dust used to form the core of planets. If we take the core accretion model for the giant planet formation, the core mass is about 10 M_{\oplus} per planet (Mizuno 1980; Pollack et al. 1996; Rice & Armitage 2003), in agreement with the rocky core mass in the solar system planets, which is 8, 10, 12 M_{\oplus} for Jupiter, Saturn and Uranus (e.g., Lodders & Fegley 1998; Guillot 1999). The mass density borne by planetary cores that arose from coagulation of dust is $\Omega_{\text{planet}} \simeq 8 \times 10^{-9}$, only 1/500 the dust abundance in eq.(5). The knowledge concerning planets is still immature and the estimates given here may be subject to revision in the future. Integrating the mass function of planets given above around the Jupiter mass, we obtain a rough estimate of the mass density of planets to be $\Omega_{\text{planet}} \approx 7 \times 10^{-7}$.

We now calculate the abundance of dust that is expected to be produced from the stellar evolution. With the Chabrier/Salpeter initial mass function, the gas shed by stars is 0.60 times the mass locked into stars with the resulting remnants given in section 1. The majority of stars have solar metallicity. We may consider that this is true even at non-zero redshift, possibly except for some galaxies very early in structure formation, as indicated by observations (e.g., Shapley et al. 2004; de Mello et al. 2004) as well as demonstrated by a numerical model for galaxy formation in the Λ CDM universe (Nagamine et al. 2001), and the metallicity estimated from high redshift quasars. The cosmic time

is short at high redshift where these considerations are more relevant. The dominant part of time relevant to star formation is at low redshift $z < 1 - 2$. Motivated by these observations, we may take the approximation that all stars have the normal metallicity the same as at low redshift. We assume that the gas shed by stellar evolution has solar metallicity on average whether gas taken into star formation is pristine or already somewhat enriched. The amount of dust produced by gas shed by stars is then

$$\begin{aligned} \Omega_{\text{dust produced}} &= \Omega_{\text{fuel}} \times 0.38 \times \langle Z \rangle \eta \\ &= 9.6 \times 10^{-6} \end{aligned} \quad (6)$$

which is about 2.5 times larger than the global amount of dust in galactic discs given in (5). The total heavy element abundance calculated with this approximation correctly reproduces the abundance observed at $z \approx 0$, which in turn is constrained by the total energy output as explored by extragalactic background light, as shown in FP04.

We also stress that a number of uncertainties in the calculation, such as those in the initial mass function, mean metallicity, and the dust/Z ratio, cancel when one compares eq. (5) with eq. (6), so that the error in the relative values is not excessively larger. The integral of star formation rate still has a significant uncertainty, but it is constrained by the observed amount of stars at $z = 0$ and the fraction of stellar mass loss with the aid of the initial final mass relation, as well as the energy output argument we quoted in section 1. We may take seriously that the gap between the two values, expected amount of dust produced and that observed in the HI region of galaxies is real.

3 DUST IN HALOES AND THE CLOSURE OF THE DUST ENTRY

This mismatch between the amount of dust that is ought to be produced in stellar evolution and that is observed implies that either we miss dust somewhere in the universe or dust produced is destroyed and not all survives to now. At the beginning, the latter may look natural since lifetime of dust is thought to be not very long (Draine & Salpeter 1979; Draine 1995; Jones, Tielens & Hollenbach 1996; Dwek 1998).

We point out, however, that the recent detection of dust reddening observed in the galaxy quasar correlation promotes us to investigate the former case. Using a large quasar sample and yet an even larger galaxy sample of the Sloan Digital Sky Survey, taking advantage of its high precision multi-colour photometry, Ménard et al. (2010, hereafter MSFR) have found that the quasar light receives reddening when it passes through the vicinity of galaxies. The colour dependence of attenuation is in agreement with the dust extinction curve known for the Milky Way, although the ratio of total to selective extinction $R_V \approx 4.9 \pm 3.2$ is not well determined. This implies that a large amount of dust is present around galaxies ranging from 20kpc to a few Mpc, which are clearly beyond galactic discs.

The projected surface density distribution of dust follows $\sim r^{-0.8} - r^{-1}$ with r the projected distance from the centre of the galaxy, similar to the galaxy mass distribution, to some 5Mpc. The column density of dust in lines of sight is very small but when integrated over a large volume this

gives a substantial total amount of dust: MSFR estimated the dust mass,

$$M_{\text{dust}} \simeq 5 \times 10^7 M_{\odot} \quad (7)$$

for $20\text{kpc} < r < r_V$ with r_V the virial radius for typical galaxies in the sample.

MSFR inferred $\Omega_{\text{halo dust}} \simeq 2.1 \times 10^{-6}$, but this should be taken as a lower limit. For the galaxy sample with median redshift of $\langle z \rangle = 0.38$ the SDSS observation samples galaxies down to $\approx 0.25L^*$. The mean luminosity of the sample is then $\langle L \rangle \approx 0.7L^*$. Assuming that the amount of dust is proportional to luminosity, the luminosity density $\mathcal{L}_r \approx 2.2 \times 10^8 h L_{\odot} (\text{Mpc})^{-3}$ means

$$\Omega_{\text{halo dust}} \approx 2.6 \times 10^{-6} \quad (8)$$

if (7) is used. MSFR shows that the distribution of dust continues to be parallel to that of dark matter associated with galaxy to several Mpc, on average beyond halfway to neighbouring galaxies. Remembering that the luminosity density, when multiplied by M/L with M the bound mass, gives $\Omega \approx 0.15$ and it is compared with $\Omega \approx 0.27$ of global mean mass density, we conclude that 45% of mass is present outside the gravitationally-binding radius of galaxies. This is demonstrated using the stacked surface matter density distribution derived from weak gravitational lensing signal, also in agreement with what we expect for the dark matter distribution in the CDM universe (Masaki, Fukugita & Yoshida 2011, in preparation). This suggests that the amount of dust we estimated must be multiplied by 1.8, including the distribution beyond the virial radius, to obtain the global abundance, if dust follows the dark matter distribution as observationally indicated in MSFR. This means that $\Omega_{\text{galaxy+vicinity dust}} \approx 4.7 \times 10^{-6}$, if the vicinity of galaxies beyond the gravitationally bound region is included.

The uncertainty in the estimate of the amount of dust outside the galaxies is admittedly large, but the order of the amount we see indicates that the amount of dust in galactic discs must be almost doubled for the total amount. This means that the total amount of dust

$$\Omega_{\text{dust}} \approx 9 \times 10^{-6}, \quad (9)$$

which is close to what is expected from stellar evolution and the amount of cooked fuels (6).

It has been discussed that dust is destroyed efficiently by sputtering in the hot environment with the time scale, $t \approx 10^5 \text{yr} (n_{\text{H}}/\text{cm}^{-3})^{-1} (a/0.1\mu\text{m})$ for $T_{\text{eff}} \sim 10^6$, the virial temperature of L^* galaxies (Draine & Salpeter 1979). In the halo environment, $n_{\text{H}} \sim 2 \times 10^{-5}$ at 100kpc (Fukugita & Peebles 2006), so that lifetime is longer than the age of the universe. It seems likely that dust in galactic haloes transported there from the galaxy during the course of its formation and evolution may survive for the cosmological time.

Our argument indicates that the longevity of dust should also apply to galactic discs. The total amount of dust we obtained is what is ought to be produced. We have no more fuels to yield extra dust. If dust would be destroyed for some reasons, it must be replenished by regeneration from interstellar matter.

We also remark that dust may be efficiently transported to outside galaxies by galactic winds. For some galaxy samples it is observed that a substantial fraction of the mass of formed stars is outflowed by galactic winds (e.g., Heckman

et al. 2002; Pettini et al. 2002; Veilleux et al. 2005; Rupke et al. 2005; Weiner et al. 2009), as also supported by plausible arguments and simulations (e.g., Madau et al. 2001; Aguirre et al. 2001; Zu et al.). Whether a large part of dust is present in some clumps, such as absorbing clouds (Ménard et al. 2007), raises an interesting problem, but in the present study, where we are concerned with the coarse-grained mean abundance, we have no resolution to this problem.

4 CONCLUSIONS AND DISCUSSION

We have shown that the amount of dust expected in stellar evolution in the cosmic time agrees with what we observe, when we take account of dust that is uncovered in galactic haloes and in the vicinity of galaxies from reddening of quasar light passing through nearby galaxies (MSFR), which roughly doubles the total amount when added to that observed in galactic discs. Namely, we are observing all dust produced in stellar evolution, which means that dominant portion of dust should survive, at least effectively for cosmic time. This contrasts to the conventional thought that lifetime of dust is much shorter than the cosmic time. This does not imply, however, that dust be intact. If it is destroyed in some processes in interstellar or intergalactic space, it must be regenerated from the gas. We emphasise that we have no extra fuels to replenish destroyed dust, meaning the closure of the cosmic energy inventory, which in turn places a significant constraint on the physics of dust. The dust amount used to form cores of planets are only 1/500 in the disc.

If the dust production were ascribed solely to core collapse supernovae, the total amount of dust we estimated means the product of $0.2M_{\odot}$ per core collapse. This mass is consistent with the prediction in some theoretical calculations (e.g., Kozasa et al. 2009; Todini & Ferrara 2001), but is 2 orders of magnitudes larger than is actually observed at type II supernovae, $10^{-4} - 10^{-3} M_{\odot}$. In our consideration we do not necessarily mean that dust is produced at the time or just after supernovae. It may in part arise from mass loss in the giant star phase before supernovae, or from gas ejected by supernovae that may condense to dust later in the interstellar space (Draine 2009).

The closure of the inventory tempts us to look at the partition more closely as to the origin of dust. From the consideration of the final versus initial stellar masses we expect that the stellar wind of stars with $1 - 8M_{\odot}$ produces 56 % of dust, where the dominant part arises from the AGB phase (see Serenelli & Fukugita 2007). Stars that end with core collapse supernovae produce 43 % of dust, including both supernovae (and after supernovae) and mass loss in the pre-supernova phase. This means that the amount of dust produced in core collapse is at most $0.08M_{\odot}$, smaller than the theoretical estimate cited above. Normalising the type Ia supernova rate to the observed value at redshift $z \approx 0$ as in FP04, we infer that type Ia supernova disrupt 5% of white dwarfs which contribute 1% of dust at the time or some time after the explosion. There is no evidence observed that type Ia supernovae yield dust.

Our consideration suggests that a substantial fraction of dust is generated from the material lost in the burning phase of evolved stars. The inventory gives useful circumstantial constraint on the production and evolution of dust,

although it does not directly suggest anything concerning the mechanisms.

ACKNOWLEDGMENT I would like to thank Bruce Draine and Peter Goldreich for encouraging me to publish this work and for stimulating discussion and useful comments improving the earlier version of this manuscript. I also thank Jim Peebles for a long-term collaboration on the cosmic energy inventory, which motivated me to seek the ‘missing dust problem’. I thank Brice Ménard for discussion, for his work to find dust in the vicinity of galaxies, and useful comments on the present manuscript. I acknowledge the support of the Ambrose Monell Foundation (2010) and the Friends of the Institute (2011) in Princeton and Grant in Aid of the Ministry of Education in Tokyo.

REFERENCES

- Aguirre, A., Hernquist, L., Schaye, J., Weinberg, D. H., Katz, N., & Gardner, J. 2001, *ApJ*, 560, 599
- Asplund, M., Grevesse, N., & Sauval, A. J. 2005, *Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis*, 336, 25
- Bahcall, J. N., Pinsonneault, M. H., & Basu, S. 2001, *ApJ*, 555, 990
- Bernardi, M., Shankar, F., Hyde, J. B., Mei, S., Marulli, F., & Sheth, R. K. 2010, *MNRAS*, 404, 2087
- Bouwens, R. J., et al. 2010, *arXiv:1006.4360*
- Chabrier, G. 2003, *PASP*, 115, 763
- de Mello, D. F., Daddi, E., Renzini, A., Cimatti, A., di Serego Alighieri, S., Pozzetti, L., & Zamorani, G. 2004, *ApJL*, 608, L29
- Draine, B. T. 2009, *Cosmic Dust - Near and Far*, 414, 453
- Draine, B. T. 1995, *Ap&SS*, 233, 111
- Draine, B. T., et al. 2007, *ApJ*, 663, 866
- Draine, B. T., & Salpeter, E. E. 1979, *ApJ*, 231, 77
- Driver, S. P., Popescu, C. C., Tuffs, R. J., Liske, J., Graham, A. W., Allen, P. D., & de Propris, R. 2007, *MNRAS*, 379, 1022
- Dwek, E. 1998, *ApJ*, 501, 643
- Fardal, M. A., Katz, N., Weinberg, D. H., & Davé, R. 2007, *MNRAS*, 379, 985
- Fukugita, M., & Peebles, P. J. E. 2004, *ApJ*, 616, 643
- Fukugita, M., & Peebles, P. J. E. 2006, *ApJ*, 639, 590
- Grevesse, N., & Sauval, A. J. 1998, *Space Science Reviews*, 85, 161
- Guillot, T. 1999, *Planet. Sp. Sci.*, 47, 1183
- Heckman, T. M., Lehnert, M. D., Strickland, D. K., & Armus, L. 2000, *ApJS*, 129, 493
- Heger, A., Fryer, C. L., Woosley, S. E., Langer, N., & Hartmann, D. H. 2003, *ApJ*, 591, 288
- Hopkins, A. M., & Beacom, J. F. 2006, *ApJ*, 651, 142
- Johnson, J. A., Aller, K. M., Howard, A. W., & Crepp, J. R. 2010, *PASP*, 122, 905
- Jones, A. P., Tielens, A. G. G. M., & Hollenbach, D. J. 1996, *ApJ*, 469, 740
- Keres, D., Yun, M. S., & Young, J. S. 2003, *ApJ*, 582, 659
- Kozasa, T., Nozawa, T., Tominaga, N., Umeda, H., Maeda, K., & Nomoto, K. 2009, *Cosmic Dust - Near and Far*, 414, 43
- Lodders, K., & Fegley, B. 1998, *The planetary scientist’s companion / Katharina Lodders, Bruce Fegley*. New York : Oxford University Press, 1998. QB601 .L84 1998,
- Madau, P., Ferrara, A., & Rees, M. J. 2001, *ApJ*, 555, 92
- Marcy, G., Butler, R. P., Fischer, D., Vogt, S., Wright, J. T., Tinney, C. G., & Jones, H. R. A. 2005, *Progress of Theoretical Physics Supplement*, 158, 24
- Mathis, J. S., Rumpl, W., & Nordsieck, K. H. 1977, *ApJ*, 217, 425
- Ménard, B., Scranton, R., Fukugita, M., & Richards, G. 2010, *MNRAS*, 405, 1025
- Ménard, B., Nestor, D., Turnshek, D., Quider, A., Richards, G., Chelouche, D., & Rao, S. 2008, *MNRAS*, 385, 1053
- Mizuno, H. 1980, *Progress of Theoretical Physics*, 64, 544
- Nagamine, K., Fukugita, M., Cen, R., & Ostriker, J. P. 2001, *ApJ*, 558, 497
- Nagamine, K., Ostriker, J. P., Fukugita, M., & Cen, R. 2006, *ApJ*, 653, 881
- Oohama, N., Okamura, S., Fukugita, M., Yasuda, N., & Nakamura, O. 2009, *ApJ*, 705, 245
- Ouchi, M., et al. 2009, *ApJ*, 706, 1136
- Pettini, M., Rix, S. A., Steidel, C. C., Hunt, M. P., Shapley, A. E., & Adelberger, K. L. 2002, *Ap & Space Sci*, 281, 461
- Pollack, J. B., Hubickyj, O., Bodenheimer, P., Lissauer, J. J., Podolak, M., & Greenzweig, Y. 1996, *Icarus*, 124, 62
- Rice, W. K. M., & Armitage, P. J. 2003, *ApJL*, 598, L55
- Rupke, D. S., Veilleux, S., & Sanders, D. B. 2005, *ApJS*, 160, 115
- Salaris, M., Serenelli, A., Weiss, A., & Miller Bertolami, M. 2009, , 692, 1013
- Serenelli, A. M., & Fukugita, M. 2007, *ApJS*, 172, 649
- Shankar, F., Lapi, A., Salucci, P., De Zotti, G., & Danese, L. 2006, *ApJ*, 643, 14
- Shapley, A. E., Erb, D. K., Pettini, M., Steidel, C. C., & Adelberger, K. L. 2004, *ApJ*, 612, 108
- Todini, P., & Ferrara, A. 2001, *MNRAS*, 325, 726
- Tremonti, C. A., et al. 2004, *ApJ*, 613, 898
- Veilleux, S., Cecil, G., & Bland-Hawthorn, J. 2005, *ARAA*, 43, 769
- Weingartner, J. C., & Draine, B. T. 2001, *ApJ*, 548, 296
- Weiner, B. J., et al. 2009, *ApJ*, 692, 187
- Zhang, W., Li, C., Kauffmann, G., Zou, H., Catinella, B., Shen, S., Guo, Q., & Chang, R. 2009, *arXiv:0902.2392*
- Zu, Y., Weinberg, D. H., Davé, R., Fardal, M., Katz, N., Kereš, D., & Oppenheimer, B. D. 2010, *MNRAS*, 1880
- Zwaan, M. A., Meyer, M. J., Staveley-Smith, L., & Webster, R. L. 2005, *MNRAS*, 359, L30